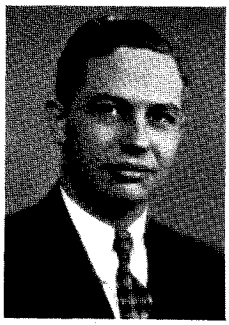
Some Aspects of Nuclear Physics



of Possible Interest in

Biological Work*

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IN selecting a title for this paper I have endeavored to choose one which would create no illusions as to its purpose or content. It is my purpose only to review (in a very elementary way) some of the aspects of nuclear physics which give promise of providing useful tools in biological research. I shall attempt to indicate a few of the types of problems to which these tools may be applied. I am not reporting any research which has been carried on in this field. I cannot claim originality for any of the suggestions I am going to make concerning biological problems, since they are all either more or less obvious or else have been proposed by various workers interested in this field.[1] Note that these are only suggestions as to possible problems to which these new tools may be applied; not predictions of any definite results which may be obtained. It is as difficult to make predictions in this field now as it would have been thirty-five years ago to predict the biological applications of x-rays and radioactivity.

Nevertheless, despite these cautious remarks, it is my own conviction, inspired by the conviction of many others better able to judge, that the discoveries of the last five years in nuclear physics are almost certain to be of far reaching importance in biology. They will greatly facilitate experimental work now going on in certain fields, and they will doubtless uncover new problems not now suspected or not open to attack by present experimental methods. Many feel that a new era in biological technique is now at hand. If this be true no further apologies need be offered for any attempt to acquaint biologists with the nature of the new tools for research which they are likely soon to be using.

We will do well to begin the discussion by listing some of the most important advances in nuclear physics in recent years.

1. The discovery, measurement, and separation of isotopes of the chemical elements (Aston, Bainbridge, Urey, *et al.*)
2. The development of machines for accelerating charged particles to very high energies (1 to 8 million electron volts)
   a. Transformer-condenser methods (Cockcroft and Walton, Lauritsen, *et al.*)
   b. Electrostatic generator (Van de Graaff, Tuve)
   c. The cyclotron (Lawrence, Livingston and Cooksey)
   d. Linear accelerators, resonance transformers, etc.
3. The transmutation of elements
   a. By natural alpha-particles (Rutherford, 1919)
   b. By artificially accelerated protons (Cockcroft and Walton, 1932)
   c. By deuterons (Lawrence, 1933)
   d. By neutrons (Feather, 1932)
4. Discovery of the positron (Anderson, 1932)
5. Discovery of the neutron (Chadwick, 1932)
6. Discovery of induced radioactivity (Curie-Joliot, 1934)

We shall pass over the field of isotopes without discussion. The heavy isotopes of hydrogen, carbon, oxygen, etc. are of great importance to nuclear physics and to biology but their use in the latter field is largely a problem of chemistry—and I shall leave it to the chemists to discuss.

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Similarly it will not be profitable in this discussion to describe in detail the experimental techniques which have been developed for producing high energy particles. It is the development of these techniques of course which has made possible all the other advances: without them it would not be possible even to discuss in a practical way the possible biological applications of nuclear physics. In fact, there would be very little nuclear physics. The time may not be far distant when a cyclotron or a Van de Graaff generator will be standard equipment in large biological and medical research centers. But our chief interest in this symposium is what these machines will do rather than how they work. The principle thing they will do is to produce transmutations of elements, and the products of these transmutations are the things which biologists may find useful. I should also mention, however, that resonance transformers and Van de Graaff machines are also suitable, and are even now in use in several medical centers, for the production of million-volt x-rays. Still higher voltages can be produced as soon as they are required, but it will be best to understand something of the effects of one-million volt x-rays before two-million volt machines are built. These machines bring x-ray energies right into the realm of gamma-rays, with available intensities which are thousands of times greater than those attainable from natural radioactive sources.

The great importance of extending radiological investigations into this region is sufficiently obvious. There is but one interesting point worth mentioning. One advantage usually ascribed to high energy x-rays is their greater penetrating power. However, this increase of penetrating power with increasing energy (decreasing wavelength) does not continue indefinitely. Above about 2.5 million volts (Mv) the penetrating power of x-rays in lead begins to decrease again, so that 3 Mv rays may actually be "softer" instead of "harder" than 2 Mv. For lighter materials than lead the maximum of penetrating power occurs at rather higher energies (10–12 Mv for Al) but the existence of this maximum must be taken into account, and may offer difficulties in the development of absorption and filtering techniques which will have to be used with these multi-million volt machines.

But million-volt x-rays are really not new tools for biological work—they are only more powerful forms of tools already familiar. We must look to the results of experiments on the transmutation of elements for the really new possibilities which nuclear physics will furnish to biology. Among these the most promising are the last two listed above, namely, the neutron and induced radioactivity, and to these subjects I shall devote the remainder of this discussion.

The Neutron

The neutron is a particle of mass 1 (actually 1.0090) and charge zero. It is one of the two fundamental building stones from which all nuclei are constructed, the other being the proton (mass 1.0076, charge +1). All nuclei are believed to be composed of these two particles and no others. Neutrons may be ejected from various nuclei by bombarding them with protons, deuterons, alpha-particles or gamma-rays. And this, in fact, is the only way in which neutrons can be made available for use in experimental work. When radon (radium emanation) is collected in a small capsule containing powdered beryllium a convenient source of neutrons is

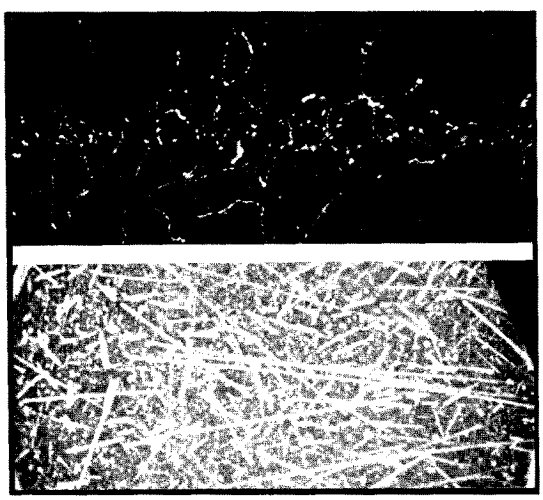

FIG. 1. The difference in biological action between x-rays and neutrons is illustrated above. The upper figure made by C. T. R. Wilson shows the tracts of electrons ejected from atoms in a cloud chamber by x-rays while the lower one made by E. O. Lawrence shows the recoil protons produced by neutrons traversing a cloud chamber.

obtained. The neutrons are ejected by the bombardment of the beryllium nucleus by the alpha-particles from radon according to the reaction

$$Be^9+He^4=C^{12}+n^1.$$

The neutrons emerge with energies up to 13.7 million electron volts (Mev) though most of them have much lower energies.[2]

While the intensity of the neutron beam obtainable from a radon-beryllium source is sufficient for many purposes, enormously more intense beams have been produced by the cyclotron. Lawrence has reported neutron beams equivalent to what would be produced only by several hundred kilograms of radium and beryllium. The reaction often used in this case is the bombardment of beryllium by deuterons, according to the reaction

$$Be^9+H^2=B^{10}+n^1.$$

What then are some of the properties of neutrons so produced? In some ways a beam of neutrons is similar to a beam of gamma-rays. They are undeflected by a magnetic field and have considerable penetrating power through heavy substances. They were, as a matter of fact, mistaken for gamma-rays in the early experiments. A further examination shows however profound differences between neutrons and gamma-rays—and these differences may have biological importance. A gamma-ray loses energy in passing through matter largely through the energy it imparts to the orbital electrons of the atoms through which it passes. A gamma-ray, being an electromagnetic radiation, has strong interaction with charged particles (electrons) and these will sooner or later rob each gamma-ray of all its energy. A neutron, however, being an uncharged particle, is not at all influenced by passing through an atmosphere of electrons. Its course can be deflected or its velocity changed only by a close encounter with the nucleus of an atom, and this is a rather rare occurrence. Even when it does occur, if the nucleus against which the neutron collides is heavy, the neutron will rebound without much loss of energy, like a golf ball from a brick wall. The neutron is scattered but does not slow down.[3] The neutron is completely absorbed only in case it enters the nucleus, and is there captured or causes the ejection of another particle. In most substances this absorption probability is very small and the neutrons therefore penetrate great thickness—e.g., several feet of lead. On the other hand some substances, for example cadmium, have a very large selective absorption for neutrons of a particular velocity—and so rapidly remove neutrons of this particular velocity from the beam.

When neutrons pass through light materials, especially materials containing hydrogen, the situation is quite different. In collision with a hydrogen nucleus, which has about the same mass as a neutron, the neutron may lose a large fraction or all of its energy, imparting it to the proton, as in the collision of two billiard balls. On the average it gives up more than half its energy at each collision, and so in about 20 collisions a 5 Mev neutron will be slowed down to thermal energies (0.1 electron volt or less). Thus a beam of fast neutrons after passing through about 6 to 10 cm of paraffin will be largely slowed down to thermal energies. At these low velocities neutrons are readily captured by a proton to form a deuteron, and so are quickly absorbed. A block of paraffin or a water cell is thus an effective barrier for neutrons—though they could easily pass through several feet of lead. The technique of handling neutron beams thus presents surprising problems, which there is not time to discuss.[4]

The problem of detecting and measuring neutron beams is also an interesting one. Since neutrons do not interact appreciably with atomic electrons they produce almost no ionization along their paths. Hence all the ordinary methods of detecting radiations (ionization chambers, counters, cloud chambers, etc.) which depend on ionization, are at first sight apparently useless. This difficulty is avoided by making use of collisions of neutrons with protons. The recoil protons produced in hydrogen-containing materials produce intense ionization, and the intensity of this can be taken as a measure of neutron intensity. The length of the recoil proton tracks produced in a hydrogen-filled cloud chamber can be used as a measure of the neutron velocities.

Still another method of detection is to make use of the disintegrations produced by neutrons in which alpha-particles are ejected, the alpha-particle ionization then being measured. The boron reaction is particularly useful:

$$B^{10}+n^1=Li^7+He^4.$$

This reaction is particularly efficient for low energy neutrons, for which the proton recoil ionization cannot be used. An ionization chamber lined with boron or filled with boron fluoride gas is widely used for the detection of neutrons.

Finally neutrons may be detected and measured by the amount of induced radioactivity they produce in certain materials such as silver.

It is evident from what has been said that the process by which a neutron loses energy in passing through matter is quite distinct from the processes by which gamma-rays or x-rays are absorbed. The latter give their energies to electrons while neutrons give their energy in appreciable quantities only to protons or other light nuclei. Electrons produce relatively small ionization over a long path; protons produce intense ionization over a short path; carbon nuclei, still more intense ionization over a still shorter path. Since it is to be expected that biological effects on individual cells will depend more on ionization *density* than total number of ions, it will be rather expected that neutrons will be more biologically effective than gamma-rays or x-rays of the same intensity. Preliminary experiments by Lawrence at California and by Zirkle of the Johnson Foundation indicate that this is indeed the case. Certainly this matter should be further investigated with great care and at once. As a matter of fact many experiments on neutron effects on both plant and animal tissue are now in progress, and there will be plenty of work in this field for many years to come.

There are difficulties in comparing neutron and x-ray effects which ought to be pointed out. X-ray doses are commonly measured in terms of the ionization produced in a standard chamber. Certain types of x-ray ionization chambers however may show almost no ionization for a neutron beam. A chamber used for neutrons must be lined with paraffin or Bakelite or other hydrogen-containing materials. The amount of ionization produced by a given beam will then depend greatly on the amount and arrangement of the materials introduced. Thus an x-ray and a neutron beam which produce equal ionization in one chamber will produce quite different effects in another one differently constructed. And the difference will depend on the energy (voltage) of the x-ray beam and the speed of the neutrons. On just what basis then can one say that neutrons are more effective than x-rays, or *vice versa*, unless there is some way of comparing intensities? Up to the present time each worker in this field has in general used a different type of ionization chamber, but in each case one has been chosen in which it was believed that the proton-recoil ionization would be comparable to what would be produced by the neutrons in biological materials. The results of different workers may be expected to be qualitatively comparable but it will soon be desirable to develop methods of quantitative measurement of neutron intensities relative to some arbitrary standard.

There is another important effect of neutrons which may be of biological interest. Both slow and fast neutrons are very effective in producing nuclear disintegrations, and in a large number of cases the disintegrations lead to products which are radioactive. (We shall have something to say about such materials later on.) In some cases also these disintegration reactions are accompanied by penetrating gamma-rays. A neutron is thus a "triple threat man" since in passing through biological materials it may simultaneously (1) produce recoil protons or other nuclei, (2) create radioactive atoms, (3) excite gamma-rays. It may be necessary to treat individually the biological results of these three processes. In most cases it seems likely that the first will be most important since disintegration probabilities are less than collision probabilities in general. And the elements for which the disintegration probability (giving rise to gamma-rays or radioactive products) is high are not materials commonly present in biological tissues, e.g., cadmium, samarium and boron. Nevertheless one should be on the lookout for cases in which neutrons produce effects on materials containing very little hydrogen, which may be due to disintegrations rather than collisions. In the case of very slow neutrons (energies of a few electron volts or

less) recoil ionization will be absent and their effects (if any) will be due solely to disintegrations.

It is possible that this property of neutrons of converting certain elements into their radioactive

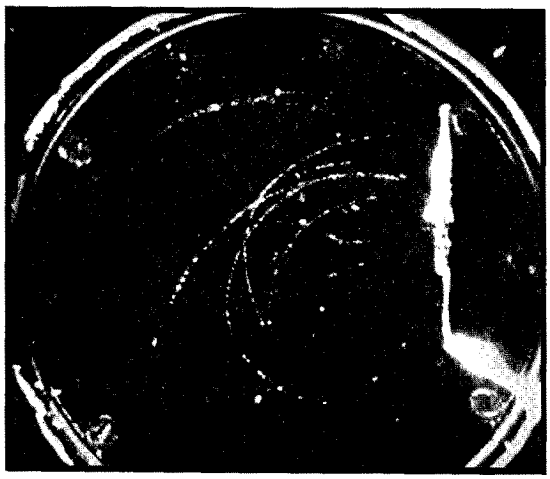

FIG. 2. Cloud chamber photograph showing the emission of positrons by radioactive nitrogen which was produced when the carbon plate shown at the right was bombarded by 900,000 electron-volt protons.

isotopes may be turned to good use. It might, for example, prove useful to direct a slow neutron beam at certain regions in the body and convert some of the elements present there into radioactive isotopes, whose radioactivity would remain for several hours after the neutron exposure had ceased. Since almost every element may be made radioactive by neutrons there are many possibilities to be considered. And this brings us directly then to a discussion of the possible uses in biological work of artificially produced radioactive materials.

Induced Radioactivity

It was in January 1934 that the Curie-Joliots reported that certain targets bombarded by alpha-particles continued to emit positrons for some time after the bombardment ceased. This positron activity was found to decay exponentially with time, just as in the case of the natural radioactive materials. By 1934 nuclear physics technique was quite well developed so that further studies of this induced radioactivity were undertaken at once by many laboratories. And now, a little over three years after the first announcement, over 220 radioactive isotopes are known, including practically every element of the periodic table and some beyond the end of the table. (Radioactive isotopes of elements of atomic number 93, 94, 95 and 96 are now known.)

The existence of these radioactive isotopes is easily understood. Each element in the periodic table has only a limited number (between 1 and 11) of stable isotopes which are found in nature. Thus fluorine has but one stable isotope, F^{19}; oxygen has three with weights, 16, 17, 18; and so on throughout the table, the heavier elements in general tending to have a larger number of stable isotopes. It is easy to see that many nuclear disintegration processes may give rise to isotopes of a particular element which are not found naturally and hence are presumably unstable. Thus one can produce F^{17}, F^{18} and F^{20}, all of which are unstable. Such atoms can in general convert themselves into stable ones by the ejection of a nuclear particle, and they will do so in the course of time. In most cases this is accomplished by the ejection of a positive or negative electron.[5] These electrons are expelled usually with considerable energy and the ionization they produce is readily measured. Each unstable atom has a certain probable lifetime, which is shorter the more unstable its nuclear structure. So, just as in the case of a large population of individuals, the number "dying" per unit time is proportional to the total number "living." And if none were being born the total population would decrease exponentially with time. The period or half-life is the time required for the number living (and also the death rate) to decrease to half its original value. This is just the law which governs the radioactivity of the natural radioelements, such as radium.

As an example if a C^{12} nucleus should capture a proton the resulting nucleus would be N^{13}, the charge and mass both being increased by 1. But N^{13} is not among the stable isotopes of nitrogen, though it could convert itself into the stable C^{13} by emitting a positron. This is what happens and it is found that N^{13} has a half-life of about 11 minutes. That is, if a large number of N^{13} atoms is formed at a given time the number of positrons emitted per second by the whole group falls to half its value in each succeeding 11 minute interval. It is in general possible by some nuclear

process to produce from one to six or more radioactive isotopes of every element in the periodic table (except hydrogen), and in many cases a particular isotope may be produced by several different nuclear reactions. As an example the radioactive Na^{24} with a period of 14.8 hours may be produced by bombarding the stable Na^{23} by either neutrons or deuterons, by bombarding Al by neutrons, or by bombarding Mg by neutrons or deuterons; five reactions in all. The properties of Na^{24} are the same no matter how it is produced. On decay the Na^{24} atom emits a negative electron and becomes stable Mg^{24}.

A few of the radioactive isotopes of some of the elements which occur commonly in biological materials are listed in Table I. The last column

TABLE I. *Some typical radioacitve isotopes.**

Atomic Number	Element and Mass	Emitted Particle	Stable Product	Half-life	Produced by
6	C^{11}	+	B^{11}	20.5 min.	B-*d*-*n*, B-*p*-γ
	C^{14}	−	N^{14}	? 3 mo.	N-*n*-*p*
7	N^{13}	+	C^{13}	11 min.	B-α-*n*, C-*d*-*p*, C-*p*-γ
8	O^{15}	+	N^{15}	126 sec.	N-*d*-*n*, N-*p*-γ
11	Na^{24}	−	Mg^{24}	14.8 hr.	Na-*d*-*n*, etc.
12	Mg^{27}	−	Al^{27}	10.2 min.	Mg-*d*-*n*, Al-*n*-*p*, —*g*-*n*-γ
15	P^{32}	−	S^{32}	14.5 days	P-*d*-*p*, S-*d*-α, P-*n*-γ, etc.
16	S^{35}	−	Cl^{35}	80 days	Cl-*n*-*p*
17	Cl^{38}	−	A^{38}	37 min.	Cl-*d*-*p*, Cl-*n*-γ, K-*n*-α
19	K^{42}	−	Ca^{42}	12.2 hr.	K-*n*-γ, K-*d*-*p*, etc.
20	Ca^{45}	−	Sc^{45}	2.4 hr.	Ca-*n*-γ, Ca-*d*-*p*, T-*n*-α
26	Fe?	?	Co	47 days	Fe-*d*-*p*
53	I^{128}	−	Xe^{128}	25 min.	I-*n*-γ
80	Hg^{205}	−	Tl^{205}	40 hr.	Hg-*n*-γ
82	Pb^{209}	−	Bi^{209}	8.5 days	Pb-*d*-*p*

* For a complete tabulation, see Livingston and Bethe, Rev. Mod. Phys. **9**, 359 (1937).

indicates how the isotopes are produced. For example the notation B-*d*-*n* opposite C^{11} indicates the bombardment of boron (B) by deuterons (d) with the ejection of a neutron (n), the reaction being

$$B^{10}+d^2\rightarrow C^{11}+n^1.$$

The other notations are similar, the symbols p, d, n, α, γ standing respectively for proton, deuteron, neutron, alpha-particle (He nucleus) and gamma-ray. In general the bombarding particle must have an energy of from one to five million electron volts. To produce reasonable amounts of radioactive material intense beams of such particles must be available. This requires a cyclotron or some form of high voltage equipment.

The possibilities of using these materials in particular biological problems are so numerous that we can mention only a few by way of illustration. The more obvious possibilities (others are certain to come) may be grouped in two classes.

1. Therapeutic uses.—Radioactive isotopes of suitable elements may be injected into the body or directly into the organ to be treated. If it is found (and this requires much careful study) that the radiations they emit have definite therapeutic effects, then it is possible that induced radioactive isotopes may be more conveniently and effectively used than the naturally radioactive materials. Of particular interest is the possibility of selective irradiation of various organs of the body through the use of radioactive isotopes of elements which happen to be concentrated in those organs either under normal or diseased conditions. Thus one would use radioactive calcium or phosphorous for bone treatment, radio-iodine for the thyroid, etc., the active material going automatically to the spot where it is needed.

The clinical applications of these materials are thus both important and possibly spectacular. For this reason they have been perhaps prematurely hailed as a new boon to medicine. They certainly open up new possibilities, but their practical value is yet to be demonstrated and this will require a long period of careful research.

2. Tracing.—From the viewpoint of fundamental biology the use of radioactive materials as tracers is of far more interest than the therapeutic uses. In this field there are almost unbelievable possibilities which represent the most biologically promising of all aspects of nuclear physics. A prominent physiologist is quoted as stating his belief that the technique of using radioactive materials as tracers in biology may open a new era in that subject in as fundamental a way as did the invention of the microscope. The microscope made it possible to follow individual cells—the radioactive isotopes make it possible to follow individual atoms.

The uses to which this tool could be put are so many that it is as yet difficult even to classify them. Almost any chemical or biological problem in which it is desirable to follow the course of particular elements or compounds through a given system should be open to attack by this method. I will mention a few such problems

which happen to have come to my attention for purpose of illustration.

1. The role of phosphorus in bodily metabolism.[6] Phosphorus is an extremely important element to both plant and animals; phosphates appear in the teeth and bones, and the internal organs contain phosphorus in the form of organic compounds, such as the phospholipids. Many important questions arise, some of which can be answered by chemical methods and some not. How much of the phosphorus intake at a given time actually reaches the bones and teeth? How long after intake does it arrive at a given point? How rapid is the replacement? By what path through the bodily organs does it arrive? How are all of these things affected by abnormal conditions of diet or of disease? All of these questions and more can be answered by administering radiophosphorus—in the food or otherwise—and then following the radioactivity as it appears and disappears in various organs, the blood, the bones or teeth. Radiophosphorus (P^{32}) can be made in fairly strong samples by deuteron bombardment of ordinary phosphorus. The radiophosphorus can be combined into any compound after it is activated, and can therefore be fed or injected in the most convenient form. The half-life of P^{32} is about 14.8 days, so the activity of a given strong sample may be followed for many months. It decays with the emission of an electron, going to S^{32} which itself is probably harmless but in any case would be formed in amounts far too small to produce observable effects. By periodically testing the activity of samples taken from various parts of the body—either during the life of the animal or after killing and ashing—the amount and rate of phosphorus arrival may be determined with considerable precision. The many possibilities are sufficiently obvious as to require no further discussion before this group. Some work along this line has already been undertaken at various laboratories, with preliminary results which show clearly the power, accuracy and feasibility of the method. Some surprising results concerning phosphorus mobilization during certain diseases have already been indicated. I shall have to leave them to be discussed by those more familiar with biology than I am.

It is evident that similar studies could be made with almost any other element of interest; calcium, potassium, iodine, iron, etc. The only question which arises is whether there exists a radioactive isotope of the element in question whose period is sufficiently long to make the studies feasible. Here of course the physicist is somewhat helpless. He can make radioactive isotopes at will, but he has no control over the period of the resulting product; he must take what comes. Each isotope has its own characteristic period, determined by its own nuclear instability. The only hope is, if suitable periods of certain elements are not now known, that new isotopes will some day be discovered which are better adapted for such work. Nature has been fairly kind in this respect in providing so many periods of suitable length, and you may be sure that physicists will be busy for some time to come finding new ones.

2. Evidently a similar technique instead of being used on the body as a whole may be applied to studies of metabolism within individual organs, in nerves or muscles, even in individual cells. Many physiologists have already recognized these possibilities, and some have already planned programs along this line.

3. As the chemical nature of viruses, of hormones, and of various gland secretions become better known it should be possible to follow the behavior of these important but elusive agents, or to gain further information about their chemical composition.

4. There are many purely chemical or biochemical problems to which the tracing technique would seem applicable. Studies of chemical changes accompanying respiration would seem to be possible with the use of radio-oxygen—though the known periods unfortunately are rather short. The three-month period of carbon should, however, be extremely useful where CO_2 or organic compounds are involved. The possibility of tracing individual carbon atoms in various organic reactions might well open up a new field in organic and biochemistry.

I think these few examples will serve to illustrate the many possibilities—some of which will lie along lines which no one can now forsee.

From what has been said you will see that the

power of the radioactive tracing technique results from the following fortunate facts:

1. Radioactive isotopes of an element are chemically identical with the stable isotopes and will therefore behave in precisely the same way in all chemical or biological processes.

2. The active isotopes can be detected in extremely small quantities. In some cases it is possible to detect the presence in a given sample of as few as 1000 atoms of a given isotope. The presence of a million atoms would give accurately measureable results. This sensitivity results from the fact that impulse counters of various types, such as the Geiger-Müller tube counter, will register each individual β-ray (+ or − electron) entering it. If the geometrical conditions are properly chosen, from 0.1 to $\frac{1}{2}$ of all the β-rays arising in a given sample may be made to enter the counter. The fundamental law of radioactive decay is that the number of disintegrations occurring per second is proportional to the total number of atoms present, i.e.,

$$dN/dt = -\lambda N,$$

where $\lambda = 0.693/T$ where T is the half-life in seconds. Thus for $T = 1000$ sec. $= 17$ min. and for $N = 1000$

$$dN/dt = 0.693 \text{ disintegrations per sec.}$$
$$= 41.5 \text{ per minute.}$$

This is an observable number, even if only 1/10th of the β-rays produced enter the counter. In the case of P^{32} it is easy to prepare samples giving more than 10^6 disintegrations per minute or about 20,000 per sec. Since $T = 14.8$ days $= 1.3 \times 10^6$ sec., we find $N \leqq 3 \times 10^{10}$ radioactive atoms. This is only about 10^{-6} microgram. And if 0.01 percent of this amount appeared in any sample taken from an organism it could still be detected.

3. While it is possible that the presence of radioactive material in large quantities in certain organs might have definite biological effects on them due to the radiations emitted, and thus give abnormal results in metabolism experiments, it seems evident that in most cases the doses given may be made sufficiently small as to preclude any important effects due to the radiation itself.

4. Finally—and this should be strongly emphasized—the technique of detecting and measuring the radioactivity of any material is simple and capable of good precision. And when one recalls the days or weeks of work required to make a quantitative chemical analysis of substances containing a few micrograms of the element of interest, and the utter hopelessness of detecting changes involving only 10^{-12} to 10^{-14} grams, one sees the radioactive technique as child's play. And when one recalls that this relatively simple technique not only detects these small quantities of material, but actually distinguishes between the atoms already present (which were not radioactive) and those introduced at a particular time (which are) the possibilities become quite exciting. It is almost as though each individual atom carried a red flag to herald its presence. (It is even better than this since we know too little of the biological effects of red flags!)

The most common instrument which will likely be used in such investigations is the Geiger-Müller tube counter. This device, undoubtedly familiar to you, consists of a conducting cylinder along the axis of which is suspended a fine wire. A potential difference of the order of 1000 volts is applied between them. The whole is enclosed in a gas-tight envelope filled with air or other gas at a pressure of a few cm of Hg. A thin window must be provided for the entrance of slow β-particles. The counter wire is connected to a two- or three-stage amplifier which feeds a loud speaker or suitable registering equipment. The entry of a

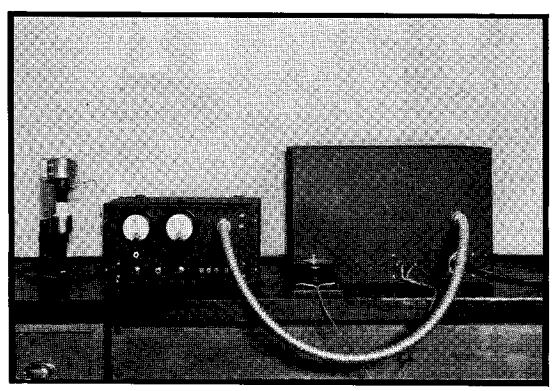

FIG. 3. The new biological "microscope" a Geiger-Müller tube counter used at the University of Rochester for biological work with radioactive materials.

β-ray into the cylinder causes a click in the speaker, or the pulse may be used to operate a mechanical register. Counter tube, rectifier, amplifier and registering device may all be contained in a box the size of a small radio set.[7] Observations consist merely in determining the number of registrations per unit time. Unfortunately such counters respond also to radioactive impurities which are always present in the air and in solid materials of the counter itself; and they also respond to cosmic rays. This means there will be a background of from 5 to 25 counts per minute which must be carefully determined and subtracted from the total observed with the source in place. It is this background which limits the ultimate sensitivity of the device, for the source being tested should produce a number of counts per minute at least as large as the background. Statistical fluctuations become important for low counting rates but can be reduced by extending the time of counting. A total of 10,000 counts must be made if the precision is to be as high as 1 percent, but only 100 counts will give 10 percent precision.

It is thus evident that simple readings of a clock and a registering device plus a little arithmetic is all that is involved in following atoms from place to place through even a complex biological system. It has been the experience that biologists who use this technique for the first time become wildly excited over the relatively simple way in which studies of most fundamental importance can be carried out. I shall expect this experience to be often repeated during coming years.

References

1. I am particularly indebted to Professor E. O. Lawrence, with whom these problems have been discussed in some detail.
2. The kinetic energy which a particle of charge e (electrostatic units) acquires in falling through a potential difference of V volts is given by the relation K.E. $= Ve/300$. An uncharged particle such as the neutron which has the same kinetic energy which an electron (or proton or any other single charged particle) would acquire in falling through a potential difference of 1 Mv is said to have an energy of 1 Mev.
3. *Inelastic* scattering (slowing down) of fast neutrons by heavy nuclei has recently been discovered at Cornell.
4. For a full account see Rasetti, *Nuclear Physics* (Prentice-Hall, 1936).
5. Electrons and positrons do not exist as such in the nucleus, but they may be created by the conversion of a proton into a neutron and a positron, or by the conversion of a neutron into a proton and an electron, the proper amount of energy being supplied or released.
6. The author is indebted to Dr. Wm. F. Bale of the University of Rochester School of Medicine for outlining the uses of radiophosphorus.
7. For further discussion and references see Harnwell and Livingood, *Experimental Atomic Physics* (McGraw-Hill, 1933) p. 412.

The cultural claims of science rest on the social fact that the use and misuse of science immediately affect the everyday life of every citizen in a modern community.—LANCELOT HOGBEN